

# Atomic Carbon in the Envelopes of Carbon-Rich Post-AGB Stars

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## ABSTRACT

Atomic carbon has been detected in the envelopes of three carbon-rich evolved stars: HD 44179 (=AFGL 915, the ‘Red Rectangle’); HD 56126; and, tentatively, the carbon star V Hya. This brings to seven the number of evolved star envelopes in which CI has been detected. Upper limits were found for several other stars, including R CrB. CI was not detected in several oxygen rich post asymptotic giant branch (AGB) stars (OH231.8+4.2, for example), although it is detected in their carbon-rich analogues. Two trends are evident in the data. First, circumstellar envelopes with detectable CI are overwhelmingly carbon rich, suggesting that much of the CI is produced by the dissociation of molecules other than CO. Second, the more evolved the envelope away from the AGB, the higher is the CI/CO ratio. The oxygen-rich supergiant star  $\alpha$  Ori remains the only oxygen rich star with a wind containing detectable CI.

These data suggest an evolutionary sequence for the CI/CO ratio in cool circumstellar envelopes. This ratio is small (a few %) while the star is on the AGB, and the CI is located in the outer envelope and produced by photodissociation. The ratio increases to about 0.5 as the star evolves away from the AGB because of the dissociation of CO and other carbon-bearing molecules by shocks caused by the fast winds which appear at the end of evolution on the AGB. Finally, the ratio becomes  $\gg 1$  as the central star becomes hot enough to photodissociate CO.

## 1. Introduction

This paper reports a search for the  $609\ \mu\text{m}$  ( $492.1607\ \text{GHz}$ )  $^3\text{P}_1 \rightarrow ^3\text{P}_0$  line of CI in the envelopes of ten evolved stars, with detections in three (HD 44179, HD 56126, and, tentatively, V Hya). These observations provide insight into the evolutionary status of the stars.

The CI(1–0) line is a useful probe of the cold interstellar medium (Phillips and Huggins 1981, Keene 1995) because it originates in almost all cases in photodissociation regions in which the dominant gas-phase carrier of carbon changes from CO to CII via CI. It is widely observed from the photodissociation regions in dense molecular clouds which are adjacent to star formation regions and from the diffuse edges of molecular clouds where the interstellar radiation field dissociates the molecular species in the cloud (Keene 1995).

CI(1–0) emission has also been observed in several circumstellar envelopes around luminous evolved late-type stars. These envelopes are produced by mass loss from cool red giant and supergiant stars, and chemical equilibrium calculations show that gas-phase carbon is probably entirely associated into CO and other molecules in the stellar atmosphere, and hence in the material leaving the stars. Circumstellar envelopes are a particularly interesting type of molecular cloud because the radial distribution in the envelope contains information both on the mass loss history of the star and on the effects of photochemistry due to the diffuse interstellar radiation field (Glassgold 1996). Further, the central stars are evolving rapidly, and much of the circumstellar material is destined to be ionized as the star evolves away from the Asymptotic Giant Branch (AGB) and towards the white dwarf stage.

CI(1–0) emission has to date been detected in three circumstellar envelopes and four planetary nebulae, and its likely origin is different in different cases:

- (1) CI(1–0) emission has been detected from planetary nebulae which still contain

part of their circumstellar material in molecular form: AFGL 618 (Young 1997) whose CI content is roughly equal to that of CO; NGC 7027 (Young et al. 1999), also with a similar ratio of CI/CO: and the Ring and Helix nebulae (Bachiller et al. 1994; Young et al. 1997), where  $n(\text{CI}) \gg n(\text{CO})$ . The CI in these objects is likely to be mostly due to photodestruction of CO by hot ultraviolet photons from the central star (Young 1997). AFGL 618 is a very young planetary nebula; its central star is of type B0 and most of its mass is in neutral form. NGC 7027 is more evolved and has a much hotter central star, but more than 50% of its mass is still in neutral form, while the Ring and Helix nebulae have very hot central stars and almost all of their mass in ionized form (Huggins et al. 1996). All of these nebulae have  $\text{C/O} > 1$  (Loup et al. 1993 and references therein; Cox et al. 1998; Kholtygin 1998; Kwitter and Henry 1998).

(2) The CI(1–0) emission from the oxygen-rich supergiant  $\alpha$  Ori (Betelgeuse) shows that the CI abundance is about five times as high as the CO abundance (Huggins et al. 1994; van der Veen et al. 1998). The hydrogen in this envelope is also mostly or entirely in atomic form (Bowers and Knapp 1987) due to the star’s relatively high effective temperature (3500 K) and partially-ionized chromosphere (Newell and Hjellming 1982; Wirsich 1988).

(3) The CI emission from the nearby carbon star IRC+10216 (Keene et al. 1993; van der Veen et al. 1998) appears to be distributed in shells of about 15'' and 45'' radius. Keene et al. (1993) show that it is likely that the CI in this envelope is due to photodissociation of carbon-containing molecules ( $\text{C}_2\text{H}_2$  for the inner shell and CO for the outer shell) by the interstellar radiation field, and that the gas leaving the star is almost entirely molecular.

(4) CI has been detected in the carbon-rich Egg Nebula, AFGL 2688 (Young 1997). The central star is hotter than AGB stars and is evolving away from the AGB, but is not yet hot enough to ionize the surrounding circumstellar material.

The envelopes in which CI emission has been detected are, with the exception of

IRC+10216, around stars hotter than about 2500 K - 3000 K, the typical temperature of AGB stars. They are also, though not entirely, carbon-rich. Guided by these results, we made a search for CI emission at the Caltech Submillimeter Observatory in ten circumstellar envelopes, with emphasis on stars with temperatures higher than those on the AGB, including some post-AGB stars. We also included two evolved stars, R CrB and  $\alpha$  Her, which are known to be losing mass or to have lost mass in the past, but from which CO emission has never been detected. In addition, the CO(4–3) line was observed in most of these stars.

The observations and results are described in the next section. Section 3 uses models of the circumstellar envelopes to derive the CI content, and the results for the individual stars are discussed in detail.

The results of the present paper are combined with those from the literature in Section 4 to discuss the evolution of AGB stars as probed by the CI line. The conclusions are also given in this section. Appendix A summarizes CI observations of evolved stars accumulated in 1994 - 1996. CI emission was not detected in any of these stars.

## 2. Observations and Results

### 2.1. Observations

The basic data for the 13 evolved mass losing stars for which the CO(4–3) and/or CI(1–0) lines were observed are listed in Table 1. The positions were taken from the Hipparcos catalogue (Perryman 1997; Perryman et al. 1997): from radio interferometry observations: or from the SAO catalogue. All of the positions have an accuracy better than 1". Also listed is the spectral type of the star, usually taken from SIMBAD or from Loup et al. (1993). Column 5 contains the chemistry of the circumstellar envelope (C = carbon

star, O = ‘oxygen’ star, with  $n(\text{O}) > n(\text{C})$ ) from Loup et al. (1993), and Column 6 the distance in parsecs.

The observations of the 492.1607 GHz ground-state fine structure ( $^3\text{P}_1 - ^3\text{P}_0$ ) line of CI were made on the nights of March 24 - 28 1998 using the 10.4 meter Robert B. Leighton telescope of the Caltech Submillimeter Observatory on Mauna Kea, Hawai‘i. The weather was superb throughout the observing run, with zenith opacities at 220 GHz of  $\tau_o \leq 0.03$ , corresponding to  $\tau_o(492 \text{ GHz}) \leq 1$ . The observations were made using a liquid helium cooled SIS junction receiver with a double-sided system temperature of about 200 K. The CI line was observed in the lower sideband with the image sideband at +3 GHz. The CI line lies in the wings of a strong atmospheric water vapor line at 487 GHz, and in this configuration the sidebands see more or less the same atmospheric opacity. The correction for the different atmospheric opacities in the two sidebands was estimated to be about 3% for excellent weather conditions, and is small enough to be ignored.

The spectral lines were measured using an acousto-optic spectrograph (AOS) with a bandwidth of 500 MHz over 1024 channels. The spectrometer frequency and spectral resolution were calibrated using an internally- generated frequency comb, and the velocity scale is corrected to the Local Standard of Rest (LSR). The spectral resolution was measured to be  $\sim 0.65 \text{ km s}^{-1}$ .

The telescope half-power beamwidth is  $15''$  at 492 GHz. The observations of each star were made by chopping between the star position and an adjacent sky position with the secondary mirror, using a chop throw of  $60''$  in azimuth at a rate of  $\sim 1 \text{ Hz}$ . Pairs of chopped observations were made with the source placed alternately in each beam. The spectral baselines resulting from this procedure are linear to within the r.m.s. noise for all observations. The temperature scale and atmospheric opacity were measured by comparison with a hot (room temperature) load. The line temperatures were corrected

for the atmospheric opacity and the main beam efficiency (measured to be 45% at 461 GHz using continuum observations of Venus) to the Rayleigh-Jeans equivalent main-beam brightness temperature  $T_{\text{MB}}$ .

Before the CI line was observed for each star, the receiver was tuned to the frequency of the nearby CO(4–3) line at 461.0408 GHz, to measure the telescope pointing offsets using the CO emission either from the star itself or from a nearby CO-bright star. In the process, a CO(4–3) line profile was obtained for each star.

## 2.2. Results

Not all of the 13 stars were observed in both lines. Only the CO(4–3) line profile of IRC+10216 was observed for comparison with the CI(1–0) observations by Keene et al. (1993). The CO(4–3) emission from RY Dra is weak, and no attempt was made to observe the CI(1–0) line. The CO(4–3) observation of IRAS 20000+3239 was made in worsening weather conditions, which ended the observing run before any useful CI(1–0) data could be obtained. CO(4–3) emission was not observed towards R CrB or  $\alpha$  Her; many observations of the CO lines towards these stars have been made (e.g. Wannier et al. 1990; Nyman et al. 1992), always with negative results. The other stars were observed in both lines.

After correction for the main beam efficiency of 45%, the data for each star were co-added and a linear baseline subtracted from regions of the spectrum assumed to be free of line emission. The results are given in Figures 1 and 2 and in Table 2. Figure 1 shows the CO(4–3) and CI(1–0) line profiles for the three stars in which the CI(1–0) line was detected, and Figure 2 the CO(4–3) line profiles for the stars in which CI emission was not detected. The velocity coverage of the CO(4–3) line profile in Figure 1 is insufficient to show the 200 km s<sup>−1</sup> outflow from V Hya (cf. Knapp et al. 1997). Observations of the

CI line from V Hya made on different nights are consistent; both detected emission near the stellar velocity. The line profile in Figure 1 is the average of the data obtained on the two nights. However, the detection of CI(1-0) emission from this star is tentative; as Figure 1 shows, there is a second feature at  $-110 \text{ km s}^{-1}$  which suggests the presence of baseline irregularities or of weak emission in an unidentified line.

Table 2 contains for each observation the r.m.s. noise in the 500 MHz AOS observation, the integrated line intensity in  $\text{K} \times \text{km s}^{-1}$ , and the peak line temperature, central velocity  $V_c$  and terminal wind outflow velocity  $V_e$ . These last three quantities were found by fitting a parabolic line profile to the data. No attempt was made to fit the complex CO(4–3) emission line from V Hya. The fit for the equally complex CO(4–3) line from OH231.8+4.2 was made to the inner part of the line profile only. The upper limits to the CI intensity for undetected stars were found by integrating the data over the velocity range of the CO emission. Where no CO emission is seen, the data were summed over  $\pm 15 \text{ km s}^{-1}$  centered on the star’s radial velocity. For stars with broad wings like OH231.8+4.2, the integration was carried out only over the velocity range of the bright inner part of the line profile.

The errors in the line intensity and peak temperature quoted in Table 2 are statistical errors only, i.e. they give the signal to noise ratio of the observations. We assume systematic errors of 10% in the calibration of the antenna temperature.

The CO and CI integrated line intensities are compared in Figures 3 and 4. The data plotted include those from Table 2 and for several other evolved stars for which both CO(4–3) and CI(1–0) observations have been made. Data for NGC 7027, and for the Helix and Ring nebulae, are not included. For IRC+10216, the CO(4–3) data are from Table 2 and the CI(1–0) data from Keene et al. (1993). For AFGL 2688, the CO(4–3) data are from Young et al. (1992) and the CI(1–0) data from Young (1997). For o Cet, the CO(4–3) data are from Young (1995) and the CI(1–0) data from van der Veen et al. (1998), adjusted for



the relative beam areas of the JCMT and CSO telescopes. There are no published CO(4–3) observations of AFGL 618 and  $\alpha$  Ori that we are aware of. The expected CO(4–3) flux as observed at the CSO for these stars is estimated from models which reproduce the intensity of the lower-lying CO lines: the CO(3–2) and CO(2–1) lines for AFGL 618 from Gammie et al. (1989) and the CO(2–1) line for  $\alpha$  Ori observed by Huggins et al. (1994). The resulting sample contains data for seven carbon stars (with six CI detections), and six oxygen stars (with one CI detection).

Figure 3 shows the CI(1–0) line intensity versus the CO(4–3) intensity. The error bars are the combination of the statistical uncertainties (Table 2) and an estimated 10% systematic uncertainty for both the CI and CO data. The uncertainties were set at 30% for the stars whose CO(4–3) line intensities were estimated from lower-lying CO transitions. Data for the stars in which CI is not detected are the ‘measured’ intensities (Table 2) with  $1\sigma$  statistical error bars.

The dotted line in Figure 3 passes through the origin and the data for IRC+10216, to illustrate a possible proportionality between CO and CI intensity when CI is produced by photodissociation. Compared to the data for IRC+10216, none of the CI non-detections is significant at the  $3\sigma$  level, i.e. were there photodissociation-produced CI in these stars, it would not be detectable. The other six stars in which CI emission is seen lie well above the line; and it is unlikely that the CI in these circumstellar envelopes is due to ‘external’ photodissociation by the interstellar radiation field.

Figure 4 shows the ratio of the CI(1–0) and CO(4–3) lines as a function of the spectral and chemical type of the central star. The  $3\sigma$  upper limits on the CI(1–0) line flux, divided by the CO(4–3) line flux, are shown for stars in which CO emission is not detected. Figure 4 suggests that the earlier the spectral type of the central star, and the more carbon rich the envelope, the greater the relative abundance of CI. However, this trend is far from

universal, and Figure 4 suggests rather that there are several different mechanisms which can produce detectable CI in a circumstellar envelope.

### 3. The CI/CO Ratio

The CO(4–3) and CI(1–0) emission from the envelopes was modeled using a line excitation/radiative transfer code for a uniformly expanding, constant mass loss rate, spherical envelope (Morris 1980, Knapp and Morris 1985, Crosas and Menten 1997). The level populations are determined by collisions with neutral species and, in the case of CO, by radiative excitation via the  $4.6\mu\text{m } v = 0 \rightarrow 1$  line. The CO extent of the envelope is assumed to be truncated by the photodissociation of CO (Mamon, Glassgold and Huggins 1988). The line profile as it would be observed by a given telescope is calculated by convolving the emergent line intensity across the envelope with a circular gaussian model of the telescope beam. The model requires knowledge of the distance, the wind velocity (which is measured from the CO profile, Table 2) and the  $4.6\mu\text{m}$  flux, found from the observations tabulated by Gezari et al. (1993). Atomic carbon has three fine-structure levels in the ground state,  $^3\text{P}_0$ ,  $^3\text{P}_1$  and  $^3\text{P}_2$ , which lie 0 K, 23 K and 62 K respectively above the ground state. The 492 GHz line corresponds to the  $^3\text{P}_1 \rightarrow ^3\text{P}_0$  transition.

The envelope modeling proceeded as follows. First, the CI(1–0) line was modeled: the free parameters are the mass loss rate, the CI/H<sub>2</sub> abundance, and the radial extent of the CI in the envelope. The CO(4–3) line was modeled with a single variable parameter, the CO/H<sub>2</sub> abundance.

Models of the three stars in which CI emission was detected, HD 44179, HD 56126, and V Hya, are discussed below in detail. The results are summarized in Table 3.

### 3.1. HD 44179, AFGL 915, the ‘Red Rectangle’

This unique and remarkable object is a carbon-rich red biconical nebula discovered by Cohen et al. (1975) with a complex red emission spectrum (e.g. Waelkens et al. 1992) containing PAH and  $\text{CH}^+$  emission (Balm and Jura 1992). The CO line flux measured by Jura, Balm and Kahane (1995) is far weaker relative to the star’s  $60\mu\text{m}$  flux density than is typical for other carbon stars (Olofsson et al. 1993). The CO line profile has two components centered at the same velocity, one with full width at zero power of about  $4\text{ km s}^{-1}$  and the other with a width of about  $12\text{ km s}^{-1}$ . Jura et al. (1995) suggest that the broad component can be associated with the mass loss outflow and the narrow component with a disk which entrains the bipolar flow. The star is a spectroscopic binary, with both stars embedded in a dusty torus or disk (van Winckel, Waelkens and Waters 1995). The extent of the bipolar outflow is  $\pm 40''$  (Waelkens et al. 1996), giving a dynamical age (assuming a distance of 330 pc and an outflow velocity of  $6\text{ km s}^{-1}$ ) of  $\sim 10^4$  years. This suggests that the disk which entrains the flow is long-lived, as discussed by Jura et al. (1995, 1997). Strong evidence for this hypothesis comes from the recent finding that the chemistry of the Red Rectangle is mixed: the broad component is carbon rich, while the narrow component is oxygen rich (Waelkens et al. 1992; Balm and Jura 1992; Reese and Sitko 1996; Waters et al. 1998). These authors suggest that the oxygen-rich narrow component is long lived and was formed during a previous phase of binary-enhanced mass loss; the star subsequently evolved to a carbon star, which is now producing the bipolar outflow (cf. the discussion of BM Gem by Kahane et al. 1998).

The spectral type of HD 44179 is given by SIMBAD as B8 - A0, but the presence of a small HII region detected via its radio frequency continuum emission (Knapp et al. 1995; Jura et al. 1997) shows that there is a hotter component in the system, with a temperature at least that of a B3 star, 25,000 K. Given the peculiar nature of the Red Rectangle, and

in particular its small central HII region and low CO/60  $\mu\text{m}$  flux ratio, it is an obvious candidate for a CI search, and as Figure 1 and Table 1 show, CI emission was indeed detected.

Is the CI(1–0) emission associated with the narrow or broad component seen in CO? Figure 5 shows the CO(4–3) and CI(1–0) line profiles from Figure 1, plotted together to allow the line shapes to be compared. The CO(4–3) line profile observed at the CSO, like the CO(1–0) and CO(2–1) line profiles observed by Jura et al. (1995), has two velocity components, with half-widths at 0 km s<sup>−1</sup> of  $\sim 4$  and  $\sim 8.5$  km s<sup>−1</sup>. The CI(1–0) line width is  $\sim 4$  km s<sup>−1</sup>, and the line profile shape comparison suggests that the CI emission is partly associated with both components, but that most of it is associated with the narrow component.

The model of the Red Rectangle was made starting with the CI(1–0) emission. The distance is poorly known: we assume the Cohen et al. (1975) distance of 330 pc, which is consistent with the Hipparcos observation of  $\pi = 2.62 \pm 2.37$  mas (Perryman et al. 1997). The best fit to the CI(1–0) emission was found with  $\dot{M} = 3 \times 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$ . Two models, one with  $\text{CI}/\text{H}_2 = 2.5 \times 10^{-5}$  and  $R(\text{CI}) = 10^{17} \text{ cm}$ , and the second with  $\text{CI}/\text{H}_2 = 10^{-4}$ ,  $R(\text{CI}) = 1.5 \times 10^{16} \text{ cm}$ , fit the data reasonably well (see Figure 6), but the latter fit is somewhat better. The narrow component of the CO(4–3) line ( $T_{\text{MB}} = 0.8 \text{ K}$ ,  $V_e = 4 \text{ km s}^{-1}$ ) was then fit by varying the CO abundance, giving  $\text{CO}/\text{H}_2 = 7.5 \times 10^{-6}$ . The CI/CO ratio in this component is thus about 13. Note that this calculation assumes a simple spherical outflow model for both broad and narrow components.

We also modeled the broad ( $V_e = 8.5 \text{ km s}^{-1}$ ) component. Although the signal-to-noise ratio of the CI(1–0) line does not rule out the presence of CI in this component, all of the gas phase C is assumed to be in CO. The mass loss rate for this component is then  $\sim 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$ , assuming that it is carbon-rich and that  $\text{CO}/\text{H}_2 = 10^{-3}$ . Thus,

$N(\text{CI}) \gg N(\text{CO})$  in the Red Rectangle, suggesting that the weakness of the CO emission relative to the  $60\mu\text{m}$  emission is due to a small CO abundance. To check this, the IRAS and published submillimeter continuum data were used to calculate the dust content of the envelope. Walmsley et al. (1991) measured the 1.3 mm flux density with the 15 m SEST, while van der Veen et al. (1994) measured the  $450\mu\text{m}$ ,  $800\mu\text{m}$  and 1.1 mm flux densities with the 15 m JCMT. The spectral index of these observations is -2.9, showing that the dust emissivity index at these wavelengths is 0.9 (the small HII region contributes negligibly to the total flux density at these wavelengths). The simple model of Knapp, Sandell and Robson (1993) was used, with  $L_\star = 10^3 L_\odot$ ,  $V_o = 7.5 \text{ km s}^{-1}$  and graphite grains, to find  $\dot{M}(\text{grains}) = 4 \times 10^{-8} M_\odot \text{ yr}^{-1}$ . The total gas to dust ratio in the envelope is then  $\sim 75$  by mass. Most of the circumstellar gas and dust in the system appears to be in the  $4 \text{ km s}^{-1}$  component, which is identified with the oxygen-rich circumstellar disk. This estimate is highly uncertain and model dependent, but provides a plausible fit to the envelope properties: we conclude that most of the gas-phase C is in CI, the gas to dust ratio is more or less normal, and the shallow emissivity index shows the presence of large grains. However, the fact that CI emission is detected from the narrow component, and that a very large majority of circumstellar shells in which CI emission is detected are carbon rich, argues that the disk component may also be carbon rich, rather than oxygen rich.

### 3.2. HD 56126

This object is likely to be a post-AGB star; its spectral type is F5Iab (SIMBAD listings) and it has a circumstellar envelope whose infrared colors suggest that mass loss has ceased within the last few hundred years (Kwok et al. 1990). Bright CO line emission (Bujarrabal et al. 1992; Knapp et al. 1998) is seen from the envelope, and its mid-infrared emission shows that it is axisymmetric (Dayal et al. 1998). The envelope is carbon rich

(Bakker et al. 1997) and the star itself has a variability period of about 12 days (Lèbre et al. 1996; Bakker et al. 1997) and is possibly an RV Tau variable. The mid-infrared spectrum shows strong emission in the Brackett series, blueshifted by about  $1000 \text{ km s}^{-1}$  (Kwok et al. 1990), showing the presence of a fast wind from the central star. The distance is not known; we use 2.4 kpc, estimated from the radial velocity,  $73 \text{ km s}^{-1}$ , assuming Galactic rotation. The CO(4–3) line intensity in Table 2 is about four times that of the CO(2–1) line observed at the CSO (Knapp et al. 1998), showing that the envelope is unresolved on a scale of  $20''$ . The CO lines are parabolic, with no sign of a fast wind - the CO(2–1) observations reported by Knapp et al. (1998) find no fast-moving molecular gas to a limit of about 2% of the brightness of the peak CO line emission.

The CI and CO lines have the same velocity and velocity width ( $V_e = 10 \text{ km s}^{-1}$ , Table 2). The CI line was modeled with  $\dot{M} = 9.5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ ,  $\text{CI}/\text{H}_2 = 4 \times 10^{-4}$ , and  $R(\text{CI}) = 5 \times 10^{17} \text{ cm}$ . This model is compared with the data in Figure 7. The CO line intensity can be reproduced by an abundance  $\text{CO}/\text{H}_2 = 10^{-3}$ , typical of values found for carbon stars (Lambert et al. 1986). At this mass loss rate and CO abundance, the radius at which half of the CO is photodissociated by the interstellar ultraviolet field is about  $4 \times 10^{17} \text{ cm}$ , using the calculations of Mamon, Glassgold and Huggins (1988). The derived CI and CO abundances are thus similar, the outflow velocities measured in both lines are the same, and the model CI radius is similar to that at which CO photodissociates. These results suggest that the CI in the HD56126 envelope is produced by photodissociation of the outflowing CO in the envelope, perhaps aided by the axisymmetric structure of the envelope. However, as Figure 3 shows, the CI/CO line strength ratio is far larger for HD 56126 than is that for IRC+10216, for which it is reasonable to assume that the observed CI is due to photodissociated carbon containing molecules. HD 56126 is too cool (spectral type F5) to produce sufficient UV photons to dissociate the CO, and there is no evidence for a hotter component (although this envelope has not been searched for radio continuum emission). A

more likely source of the CI is collisional dissociation of slow-moving circumstellar CO by the fast wind (Kwok et al. 1990).

### 3.3. V Hya

The carbon star V Hya has bright CO emission, weak CS emission and a very unusual CO line shape, with two horns and a Voigt-like line profile, quite different from the parabolic, steep sided line profile seen from almost all other AGB envelopes. In addition, the star has a fast molecular wind with an outflow velocity of at least  $200 \text{ km s}^{-1}$  (Knapp et al. 1997).

The distance to V Hya can be estimated at 380 pc assuming a standard absolute K magnitude, consistent with the upper limit to the Hipparcos parallax,  $0.16 \pm 1.29 \text{ mas}$ , Perryman et al. (1997). The velocity and spatial structure of the CO emission from the V Hya envelope is complex (Kahane et al. 1996; Knapp et al. 1997). The CS(5–4) and (7–6) lines have relatively simple shapes, and the line widths suggest an outflow velocity of  $15 \text{ km s}^{-1}$ , consistent with the width of the weak, tentatively detected CI line (Table 2, Figure 1). The CI emission can be fit with  $\dot{M} = 1.5 \times 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$ ,  $\text{CI}/\text{H}_2 = 3 \times 10^{-4}$ , and a CI shell radius of  $5 \times 10^{16} \text{ cm}$ . The fitted profile is compared with the data in Figure 8. The inner parts of the CO(4–3) profile can then be fit with  $\text{CO}/\text{H}_2 = 10^{-3}$ , giving a CI/CO ratio of 0.3.

V Hya is a cool carbon star, and there is no evidence of a hotter component in the system. It is thus unlikely that the CI is produced by photodissociation. Given the presence of the fast molecular wind and shock-excited optical line emission (Lloyd Evans 1991), a more likely mechanism for producing the CI is shock dissociation of circumstellar CO. The signal-to-noise ratio of the CI line profile is far too low to detect any fast-moving CI. J type

shocks can dissociate CO, but do not ionize carbon: the possibility of shock dissociation can be tested by searching for the [OI]63 $\mu$ m and [CII]158 $\mu$ m lines, or by the presence and line ratios of the H<sub>2</sub> ro-vibrational lines (Hollenbach and McKee 1989).

### 3.4. Non-Detections

No CI emission was detected from any of the other stars. The limit on the CI/CO ratio is not sufficient for most of these stars (Y CVn, RY Dra, X Her, 89 Her) to rule out a CI abundance similar to that of the detected stars (Figure 3). Y CVn was observed because of its unusual chemistry (it is a J-type carbon star) and because, like HD 44179, it has a low ratio of I(CO)/S(60 $\mu$ m). The cases of OH231.8+4.2 and AFGL 2343 are more interesting. OH231.8+4.2 is, perhaps, an oxygen-rich analogue to V Hya: it has a cool central star and no internal source of photoionization, a fast molecular outflow, and shock-excited optical line emission (Reipurth 1987). Unlike V Hya, OH231.8+4.2 has much cooler IRAS colors and is oxygen rich. The lack of detection of CI emission from OH231.8+4.2 is then consistent with the weak emission from V Hya, given the different envelope chemistries. AFGL 2343 is an oxygen-rich post-AGB G5 supergiant, with a very high mass loss rate. The star is less evolved than its closest carbon star analogue, AFGL 2688, and does not yet have a fast molecular wind.

Two stars which are known to be losing mass but have never been detected in the CO line are  $\alpha$  Her and R CrB. The latter star is the prototype of a very rare class; carbon-rich, hydrogen-poor, yellow giants (the spectral type of R CrB is GOIab) which at random intervals undergo a steep decline in brightness by many magnitudes due to the expulsion of dust (see Clayton 1996). R CrB is surrounded by a large dust shell 18' in diameter (Gillett et al. 1986) whose mass may be several  $M_{\odot}$ . It is a semiregular variable with several periods (Rao and Lambert 1997, Feast et al. 1997, Feast 1997), has an inner dust shell also



detected by IRAS, and has recently begun another fading episode (Walker et al. 1986). ISO observations show a featureless spectrum. Several attempts to detect CO emission from this star have proved unsuccessful (see Loup et al. 1993), as has a search for HI (Clayton 1996). Given the high effective temperature (6500 K, Rao and Lambert 1997) any gas shed by the star is expected to be atomic rather than molecular.

Considerable observing time was expended on this star; as well as the time spent in March 1998, CI observations were obtained in March 1996. No emission was detected in the summed observations at an r.m.s. level of 0.016 K (Table 2), setting a  $3\sigma$  upper limit on the CI column density of about  $2 \times 10^{15}$  cm. The failure to detect CI emission from this star could have many causes, but one of the more plausible explanations lies in the hydrogen deficiency of the star - the gas densities in any circumstellar gas may not be high enough to collisionally excite the transition.

#### 4. Discussion and Conclusions

In this paper, we describe a search for atomic carbon in the circumstellar envelopes of evolved stars using the 492 GHz  $^3P_1 - ^3P_0$  fine structure line. CI was detected in three envelopes, those around HD 44179 (the Red Rectangle), HD 56126 and (tentatively) V Hya. Not counting evolved planetary nebulae, this brings to seven (including the transition object AFGL 618) the total number of evolved star envelopes in which CI emission has been detected. CI was not detected in sixteen other evolved stars (seven of them discussed above and a further nine in Appendix A). Of the detected stars, V Hya (tentatively detected) is at the earliest stage of evolution: it is still on the AGB and does not have hot stellar component, but is ejecting a fast molecular wind as well as a slow wind, and the CI may be produced by shocks where the fast and slow winds interact. The CI/CO ratio in this envelope is about 0.3. HD 56126 has an F5 spectral type, and is a post-AGB star. The

CI/CO ratio is about 0.4. The hottest of these three stars is HD 44179, whose spectral type is B0 - B3; CI/CO  $\sim$  13 for this object. These three stars show that a progressively larger fraction of the carbon in a circumstellar envelope is in the form of CI as the central star becomes hotter and more evolved beyond the AGB.

Tables 3 and 4 summarize the observational results to date; Table 3 lists the evolved stars from which CI emission has been detected, and Table 4 the stars in which it is not detected. Table 3 includes the four planetary nebulae in which CI emission has been detected.

Tables 3 and 4 show several trends: (1) CI is overwhelmingly detected in carbon rich envelopes. In carbon and oxygen rich envelopes of otherwise comparable properties (e.g. OH 231.8+4.2 and V Hya; AFGL 2688 and IRC+10420; HD 56126 and 89 Her), CI is detected in the carbon-rich envelope and not in the oxygen-rich envelope. This suggests that much of the CI may originate in the destruction of molecules other than CO - C<sub>2</sub>, C<sub>2</sub>H<sub>2</sub>, for example - which are easier to destroy. (2) in most stars, whatever CI is produced by external photodissociation, i.e. by dissociation by the interstellar radiation field, is either too small in quantity or is produced at too large radii (where the total gas density is low) to be detectable. (3) the presence of a hot ( $\geq$  20,000 K) central star very quickly produces significant photodissociation - the very young planetary nebulae AFGL 618 and HD 44179, both of which have hot central stars, have CI/CO  $\geq$  0.5. (4) in carbon rich post AGB stars such as AFGL 2688, V Hya, and HD 56126, detectable CI is present even before the central star becomes very hot. The first two stars have fast molecular winds, the third a fast ionized stellar wind. The indirect circumstantial evidence suggests shock production of CI. (5)  $\alpha$  Ori is, to date, unique - its surface temperature is high enough that the wind is largely atomic, but atomic gas is not detected from other supergiants (CE Tau, VY CMa) in the observed sample. (6) The gaseous component of the copious mass loss that must

occur for R CrB remains undetected.

These observations show that the CI in the envelopes of evolved stars has a variety of origins, as it does in other regions of the interstellar medium. Almost all evolved stars are cool enough that their winds are dusty and molecular, and CI is produced in these envelopes, as in other molecular clouds, by the shock- and/or photo-destruction of circumstellar molecules. The data also show the dependence of the CI content on evolution - the CI/CO ratio rises as the star evolves away from the AGB.

Some of the observations described in Appendix A were made in collaboration with Karl Menten: we thank him for allowing us to publish those observations here. We are very grateful to the director of the CSO, T. G. Phillips, for granting the observing time for this project, and to the staff for much help and advice with the observations. We thank the referee, Jocelyn Keene, and the editor, Steve Willner, for very helpful comments. This research made use of the SIMBAD data base, operated at CDS, Strasbourg, France. Astronomical research at the C.S.O. is supported by the National Science Foundation via grant AST96-15025. Support for this work from Princeton University and from the N.S.F. via grant AST96-18503 is gratefully acknowledged.

### **A. Searches for CI in Evolved Stars, 1994–1996**

This Appendix summarizes negative results for searches for CI emission from evolved stars made in 1994-1996 at the CSO. These observations were made before the CSO was equipped with its chopping secondary mirror, and so are not as sensitive as subsequent observations. The status of the CSO for these observations, and the observing methods, are as described by Young (1997).

The observations are summarized in Table 5, which gives the object, its 1950 position,

its circumstellar chemistry, the type of object, and the  $5\sigma$  upper limit to the brightness temperature in the CI(1–0) line.

The nine objects in Table 5 were observed for a variety of reasons. M 1-16 and IRAS 17243-1755 are planetary nebulae. M 1-16 is a bipolar planetary nebula, while IRAS 17243-1755 is a young planetary nebula like AFGL 618 with a small central HII region embedded in a molecular envelope - it is, however, oxygen rich. Like  $\alpha$  Her,  $\alpha$  Sco is a red giant star which is known to be losing mass, but which has not been detected in the CO lines. VY CMa and IRC+10420 are both oxygen-rich supergiant stars. The central star of IRC+10420 is an F supergiant, so this is a post-AGB star; like AFGL 2343, it may be an oxygen-rich analogue of AFGL 2688. R Leo is a nearby bright Mira for which CO observations give a fairly low mass loss rate ( $1 - 2 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ ). R Vir is a Mira variable of early spectral type. Young (1995) showed that the cooler Miras (spectral type M 6 and later) have circumstellar shells which are readily detected in the CO lines, while the warmer Miras (M5 and earlier) do not: again, by analogy with  $\alpha$  Ori, these stars may be ejecting an atomic stellar wind. Finally, the only carbon-rich object in Table 5, CIT 6, was observed because it is an evolved star with a carbon-rich circumstellar envelope whose CO emission is second in brightness only to that of IRC+10216. The failure to detect CI in this star, and the small amount of (photoproducted) CI in IRC+10216, shows that when  $n(\text{C}) > n(\text{O})$ , the excess carbon is in various carbon molecules rather than atomic form.

Table 1. Observed Stars: Basic Parameters

Star	$\alpha(1950)$	$\delta(1950)$	Sp.T.	Chem.	D(pc)	Refs
HD 44179	06 17 37.0	−10 36 52	B0-B3	C	330	1
HD 56126	07 13 25.3	+10 05 09	F5	C	2400	2
OH231.8+4.2	07 39 58.9	−14 35 44	M6	O	1300	3
IRC+10216	09 45 14.8	+13 30 41	C	C	150	4
V Hya	10 49 11.3	−20 59 05	N: C7,5	C	380	5
Y CVn	12 42 47.1	+45 42 48	C5,5	C	220	H
RY Dra	12 54 28.1	+66 15 52	C4,5	C	500	H
R CrB	15 46 30.7	+28 18 32	F8I	C		
X Her	16 01 08.8	+47 22 36	M6	O	140	H
$\alpha$ Her	17 22 22.3	+14 20 46	M5	O	120	H
89 Her	17 53 24.0	+26 03 24	F2Iab	O	1000	H
AFGL 2343	19 11 24.9	+00 02 19	G5	O		
IRAS20000+3239	20 00 02.8	+32 39 07	G8Ia	C		

Spectral types from SIMBAD listings unless otherwise noted

Chemistry from Loup et al. (1993)

H = distance from Hipparcos parallax (Perryman 1997; Perryman et al. 1997) or from other sources, consistent with Hipparcos parallax limit

Other distances: (1) Cohen et al. 1995. (2) calculated assuming Galactic rotation. (3) Bowers and Morris 1984. (4) see discussion by Jura (1994). (5) calculated assuming standard bolometric K magnitude of -8.2 (e.g. Jura 1994).

Table 2. Observational Results.

Star	Line	r.m.s. (K)	I (K km s <sup>-1</sup> )	$T_{MB}$ (K)	$V_c$ (km s <sup>-1</sup> )	$V_e$ (km s <sup>-1</sup> )	Vel. Range (km s <sup>-1</sup> )
HD 44179	CO(4–3)	0.052	7.26±0.17	0.89±0.04	+0.2±0.2	5.6±0.2	
	CI(1–0)	0.058	1.92±0.16	0.27±0.04	+0.3±0.3	5.1±0.7	
HD 56126	CO(4–3)	0.095	36.1±0.5	2.59±0.05	+72.9±0.4	10.3±0.4	
	CI(1–0)	0.053	2.82±0.23	0.17±0.02	+74.1±1.0	12.7±1.4	
OH231.8+4.2	CO(4–3)	0.100	163.5±1.1	2.89±0.03	+35.4±0.3	29.1±0.5	0–70
	CI(1–0)	0.065	−0.3±1.1	-	-	-	
IRC+10216	CO(4–3)	0.60	433.3±3.0	20.1±0.2	−25.4±0.2	15.0±0.1	
V Hya	CO(4–3)	0.10	127.3±1.1	-	-	-	-100–100
			102.9±1.1	-	-	-	-33,0
	CI(1–0)	0.038	2.45±0.17	0.11±0.02	−16.4±1.3	16.4±1.5	
Y CVn	CO(4–3)	0.088	17.3±0.3	1.45±0.05	+21.7±0.1	9.5±0.4	
	CI(1–0)	0.053	0.0±0.2	-	-	-	
RY Dra	CO(4–3)	0.106	9.5±0.4	0.61±0.05	−5.0±0.4	9.0±0.5	
R CrB	CI(1–0)	0.016	0.00±0.13	-	-	-	-20,80
			−0.23±0.05	-	-	-	-10,15
X Her	CO(4–3)	0.090	21.7±0.4	2.54±0.06	−73.1±0.2	7.5±0.2	
	CI(1–0)	0.04	0.0±0.2	-	-	-	
$\alpha$ Her	CI(1–0)	0.056	−0.017±0.20	-	-	-	

Table 2—Continued

Star	Line	r.m.s. (K)	I (K km s <sup>-1</sup> )	$T_{MB}$ (K)	$V_c$ (km s <sup>-1</sup> )	$V_e$ (km s <sup>-1</sup> )	Vel. Range (km s <sup>-1</sup> )
89 Her	CO(4-3)	0.084	3.6±0.3	0.47±0.07	-7.61±0.49	5.7±1.1	
	CI(1-0)	0.05	-0.37±0.20	-	-	-	
AFGL 2343	CO(4-3)	0.101	94.1±0.7	1.79±0.03	+99.7±0.3	36.3±0.4	
	CI(1-0)	0.059	-0.62±0.65	-	-	-	
IRAS20000+3239	CO(4-3)	0.11	7.2±0.4	0.32±0.03	+12.6±1.1	18.7±2.3	

Table 3. CI/CO for Evolved Stars with Detected CI

Star	Chem	N(CI)/C(CO)	T <sub>eff</sub>	Refs
IRC+10216	C	0.02	1250	Y97
AFGL 2688	C	0.07	6500	Y97
AFGL 618	C	0.7	30,000	Y97
NGC 7027	C	0.5	170,000	Y97
NGC 6720	C	10	110,000	Y97
NGC 7293	C	6	90,000	Y87
$\alpha$ Ori	O	5	3,500	H94,V98
V Hya	C	0.3	2650	This paper
HD 56126	C	0.4	6500	This paper
HD 44179	C	13	25,000	This paper

H94: Huggins et al. 1994

Y97: Young 1997

V98: van der Veen et al. 1998



Table 4. CI in Evolved Stars: Non-Detections

Star	Chem	Sp. Type	Refs
Y CVn	C	C5,5	1,2
R CrB	C	GOIab	1
X Her	O	M6	1
$\alpha$ Her	O	M5	1
89 Her	O	F2Iab	1
AFGL 2343	O	G5	1
OH231.8+4.2	O	M6	1
o Cet	O	M5.5e	2
NML Tau	O	M8e	2
CE Tau	O	M2Iab	2
VY CMa	O	M5Iab	2,3
R Leo	O	M7e	2,3
SW Vir	O	M7III	2
V CrB	C	C6,2e	2
TX Psc	C	C7,2	2
CIT 6	C	C4,3	3
$\alpha$ Sco	O	M1.5Ib	3
M 1-16	O	PN	3
IRAS17423-1755	O	PN	3
R UMi	O	M7	3
IRC+10420	O	F8Ia	3
R Vir	O	M4.5III	3

1. This work: observations with CSO
2. van der Veen et al. 1998: observations with JCMT
3. This Work, Appendix A: observations with CSO

Table 5. Negative Results for CSO CI Observations, 1994-1996

Star	$\alpha(1950)$	$\delta(1950)$	Chem.	Obj. Type	$T_{\text{MB}}$
M 1-16	07 34 55.2	-09 32 00	O	PN	<0.4
IRAS17423-1755	17 42 18.9	-17 55 36	O	PN	< 0.3
VY CMa	07 20 54.7	-25 40 13	O	SG	< 0.2
R UMa	10 41 07.9	+69 02 20	O	Mira	< 0.2
IRC+10420	19 24 26.8	+11 15 11	O	SG/PAGB	<0.2
R Leo	09 44 52.2	+11 39 42	O	Mira	<0.2
R Vir	12 35 57.7	+07 15 48	O	Mira	<0.9
CIT 6	10 13 10.7	+30 49 17	C	Mira	<0.4
$\alpha$ Sco	16 26 20.3	-26 19 22	O	RG	<0.4

PN = planetary nebula, Mira = Mira variable, SG = supergiant, PAGB = post-AGB star, and RG = red giant

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Fig. 1.— CO(4–3) and CI(1–0) line profiles observed with the CSO for three evolved stars in which CI emission is detected.

Fig. 2.— CO(4–3) line profiles of eight evolved stars in which CI was not detected.

Fig. 3.— Integrated intensity, in  $\text{K} \times \text{km s}^{-1}$ , of the CI(1–0) line versus that of the CO(4–3) line observed with the Caltech Submillimeter Observatory. The open symbols are observations of oxygen-rich stars, the filled symbols of carbon-rich stars. The dotted line suggests the proportionality between these two lines for stars in which the CI is produced by photodissociation.

Fig. 4.— Ratio of the intensities of the CI(1–0) and CO(4–3) lines as a function of spectral type. Inverted triangles are  $3\sigma$  upper limits for the CI line for undetected stars. Open symbols: oxygen stars. Filled symbols: carbon stars.

Fig. 5.— Comparison of the CO(4–3) (heavy line) and CI(1–0) (light line) line profiles for HD 44179, the “Red Rectangle”. The intensity scale for the CO(4–3) line has been reduced by a factor of four.

Fig. 6.— Two models (heavy line) for the CI(1–0) emission from HD 44179, the ‘Red Rectangle’, compared with the data (light line). Upper panel:  $\text{CI}/\text{H}_2 = 2.5 \times 10^{-5}$ ,  $R(\text{CI}) = 10^{17} \text{ cm}$ . Lower panel:  $\text{CI}/\text{H}_2 = 10^{-4}$ ,  $R(\text{CI}) = 1.5 \times 10^{16} \text{ cm}$ .

Fig. 7.— Comparison of model CI emission (heavy line) with data (light line) for HD 56126.

Fig. 8.— Comparison of model CI emission (heavy line) with data (light line) for V Hya.

















